Exploring to Learn and Learning to Explore

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Abstract

In respect to ecological psychology processes of attunement and calibration, this critical review focusses on how exploratory behaviors may contribute to skilled perception and action, with particular attention to sport. Based on the theoretical insights of Gibson (1966) and Reed (1996), exploratory and performatory actions have been differentiated in numerous experiments to study the perception of opportunities of action. The distinction between exploratory and performatory actions has informed the study of infant behavior in developmental psychology. In the current article, we highlight limitations with this distinction in the study of sports performers. We propose that a dynamic view of exploratory behavior would reveal how individuals develop exploratory activity that generates information about the fit between environmental properties and action capabilities. In this aim, practitioners should: (i) give learners the opportunity to safely develop exploratory behaviors even when they act outside their action boundary; and (ii) guide learners to search for more reliable information to develop exploratory behaviors that would enhance the transfer of skills to various performance contexts.

Keywords: Skill acquisition, Exploration, Ecological psychology, Perception, Action

Introduction

Exploration is the continuous and active process through which individuals reveal and pick up information during the control of action (E. J. Gibson 1988; J. J. Gibson 1979/2015). From an ecological psychology perspective, information resides as patterns in ambient energy arrays (e.g., optical, acoustic, mechanical) that specify the state of the relation between the environment and the individual. From this point of view, exploration underpins the relation between information and movement as the energy arrays are structured by the properties of the environment and the motion of the individual (J. J. Gibson 1979/2015; Mantel, Stoffregen, Campbell, and Bardy 2015; Stoffregen, Mantel, and Bardy 2017). When the information specifies relevant individual-environment relations, individuals perceive opportunities for action, that is, affordances (J. J. Gibson 1979/2015). Said otherwise, through exploratory perceptual-motor activity, individuals reveal energy arrays leading to the pickup of information about affordances that is used to adapt to the environment (E. J. Gibson, 1988).

Authors have tended to differentiate between exploratory and performatory actions (J.J. Gibson, 1966; E. J. Gibson, 1988; Reed, 1996). An underlying proposal has been that exploratory action reveals information that is subsequently utilized in the control of performatory action (e.g., Kretch and Adolph, 2016). Exploration is often considered as a period of information-gathering to satisfy an intention (Adolph, Eppler, Marin, Weise, & Wechsler Clearfield, 2000; E. J. Gibson, 1988; Kretch & Adolph, 2017). In this context, exploratory and performatory actions are often differentiated as the former is thought to precede the latter in development. Whilst such distinction has been meaningful in the developmental psychology literature when applied to other domains of psychology such as expert perceptual-motor control in sport, this has led to the development of methods that separate the reciprocity of perception-action (e.g., McGuckian, Cole, Chalkley, Jordet, and Pepping 2018). Indeed, a contemporary view of perception-action, that builds on James

Gibson's (1966) original perspective is that the process of visual perception is context-dependent and relative to the body and action capabilities of the performer (Wagman & Morgan, 2010). Although this view is well-established in ecological psychology, this important proposal is often omitted in the sports skill acquisition literature, particularly during intervention studies aimed at examining the role of exploratory movements in learning.

Given that a central tenet of ecological psychology is that perception is embedded in the continuous flow of action and vice-versa, in the current manuscript, we aim to develop a view of exploratory and performatory action that reflects an embodied-embedded approach to skilled behavior (Richardson, Shockley, Fajen, Riley, & Turvey, 2008). We argue that studying the dynamics of changes in exploration during learning could provide valuable information on how perception-action is developed, with specific consideration of how learners become more skilled at perceiving and acting in relation to affordances with respect to sport-specific behaviors (Ludovic Seifert, Komar, Araújo, & Davids, 2016). Central to this view is an affordance-based control framework (Fajen, 2005), which proposes two learning processes in the development of perception and action: (i) attunement and (ii) calibration. First, attunement is characterized by the differentiation of information that supports the pickup of more reliable patterns in the energy arrays to guide action (Fajen & Devaney, 2006; J. J. Gibson, 1966). Second, calibration consists in finding an appropriate scaling between information and action capabilities (Fajen, 2007). Indeed, as individuals' action capabilities change over time (e.g., action capabilities can change with fatigue), recalibration facilitates continuous adaptation that supports the visual control of action (Fajen, 2005, 2007). Despite the large body of literature discussing the importance of exploration to develop perception-action, exploratory activity is rarely studied in sports skill acquisition. To address this gap in the literature, we propose the need to examine the exploratory actions used to generate and scale reliable information for affordances, to better understand "how" individuals become more skilled during learning.

In sum, this critical review will focus on how exploratory activity can give rise to perception-action during the acquisition of perceptual-motor skills in sport. We will first consider the methods used in ecological psychology to investigate exploration. Although this distinction appears insightful to understand the development of action systems (Reed, 1996), we propose that these methods cannot be applied to all performance contexts. Indeed, in many complex sporting environments such as climbing (L. Seifert et al., 2018), exploratory and performatory actions can appear tightly linked in tasks where performers need to continuously adjust their relationship with the environment to guide on-going and future activity. Second, we consider the dynamics of exploratory activity during learning. In studies of expert sport populations, it is often implied that the amount of exploration decreases as performers become more attuned to the relevant properties of the environment (Mann, Williams, Ward, & Janelle, 2007). We will discuss such assumption and present exploration as a process that, under appropriate practice conditions, supports attunement and calibration, thus, continuously revealing the appropriate fit between the environment and the perceiver's action capabilities. Finally, we will present some challenges and considerations to design interventions where individuals can learn to explore. Rather than learning a specific movement, we propose that skill acquisition should focus on how performers could develop exploratory behavior: (i) that is useful in various performance contexts; and (ii) that enables maintenance of active prospective control during performatory activity.

Explore to Reach a Task-Goal: Exploration and Performance

Exploratory Actions: Explore to Perform

James Gibson (1966) proposed that perception is an active process that does not rely on passive sensory units, but on the activity of perceptual systems. Gibson differentiated exploratory (or investigative) activity achieved by these perceptual systems from the performatory (or executive) activity achieved by the action systems. Following Gibson's initial work, Reed (1996) further differentiated exploratory and performatory activities to understand the development of functional systems, which are the systems that enable individuals to use resources in their environment to achieve their goal. Reed (1996) proposed that exploratory actions are those that are aimed at scanning the environment for information whereas performatory actions are those that alter the substances and surfaces of the environment. This distinction is useful as animals, especially those like humans, with a head differentiated from the rest of the body, are able to scan their environment for information while acting in their environment. For example, during bipedal locomotion, humans have the capacity to maintain a prospective control in locomotion or to initiate other activity (Reed, 1996).

The differentiation between performatory and exploratory activity is in line with perspectives in developmental psychology (E. J. Gibson, 1988). Eleanor Gibson differentiated performatory actions from exploratory actions that are information-gathering, to understand how infants discover opportunities for action. For instance, E. J. Gibson et al. (1987) measured the visual and haptic exploration of infants in a task where they had to traverse different surfaces. Exploratory activity was defined as the period before initiation of locomotion on the manipulated surface (i.e., when the infants were leaving a starting platform). This study showed that the duration of haptic and visual exploration depended on the properties of the surfaces (whether they were rigid or not) and on the mode of locomotion that was characteristic of the infants' developmental stage. Thus, this distinction of performatory and exploratory activities appears valuable to understand how infants developed their action systems and perceive new affordances. For example, in a series of experiments, the exploratory activity of children of different ages and abilities were studied in a task requiring them to approach a slope to study whether they perceived the slope as “crossable” or not (Adolph, 1995; Adolph, Bertenthal, Boker, Goldfield, & Gibson, 1997; Adolph, Eppler, & Gibson, 1993; Adolph et al., 2000; Adolph & Eppler, 1998). In these studies, all actions (whether visual or haptic) that occurred before each child passed the edge of the slope were considered as exploratory actions. The possibilities of performatory actions are minimal in young infants as their action systems are not well developed (E. J. Gibson, 1988). Therefore, the distinction between exploratory and performatory action enables description of the links between infants’ activity and the attunement of their perceptual-motor system (Adolph et al., 1993; Eppler, Adolph, & Weiner, 1996; E. J. Gibson et al., 1987).

The distinction between exploratory and performatory actions in developmental psychology has motivated studies in the sport of climbing that have investigated the effects of anxiety on affordance perception (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008; Pijpers, Oudejans, & Bakker, 2005; Pijpers, Oudejans, Bakker, & Beek, 2006). In these works, the visual fixations and hand movements of climbers have been categorized as being either exploratory or performatory based on the actions utilized to complete the climb. If the action led to a displacement of the climber on the route, it was deemed performatory, otherwise the action was deemed exploratory. Results showed that both exploratory and performatory visual (eye) and haptic (hand) movements increased in high anxiety conditions, suggesting that the climbers performed at a level equivalent to novice performance (Pijpers, 2006). Further to climbing studies, researchers have also differentiated between exploratory and performatory actions in soccer. Specifically, in these works, studies have measured visual exploratory activity (VEA), separate from performatory actions (Jordet, 2005; Pocock, Dicks, Thelwell, Chapman, & Barker, 2019), with VEA defined as head and body movements that are used to scan the environment (pitch, teammates, and opponents) prior to receiving the ball, whereas performatory actions are those observed once a player is in possession of the ball. The differentiation between VEA and performatory action has led to the development of experimental methods that have studied VEA in response to video images presented across multiple screens, without any game-specific performatory action (McGuckian et al., 2019; van Andel, McGuckian, Chalkley, Cole, & Pepping, 2019). Thus, a methodological consequence of creating a dichotomy between exploratory and performatory actions is that researchers have studied perception and action as two separate processes, which compromises the theoretical view of Gibson (1966). Similarly, in climbing, the differentiation of exploratory and performatory hand movements has been questioned as in many instances, it is possible that movements categorized as being exploratory may actually be "failed" performatory movements (Orth, Button, Davids, & Seifert, 2016). For instance, a climber may have tried to use a handhold, but because the handhold depth was not as expected, he/she may have only touched the handhold, released it, and then used another hold. Thus, even "failed" performatory actions may have temporary performance consequences, they remain important in the process of learning to differentiate information (van Dijk & Bongers, 2014). Thus, during practice, the entire activity (i.e., both exploratory and performatory actions) contributes to their perceptual learning.

In summary, actions have tended to be categorized according to their outcomes: if they enable the performer to reach the task-goal they are performatory actions, otherwise, if they lead to the discovery of available information and preparing the performatory actions, they are related to exploratory activity. Thus, exploratory activity relates to actions that aim at gathering or scanning information before the initiation of a performatory action. Considering the reciprocity of perception and action, the study of prospective control with the distinction between "action to perceive" (exploratory activity) and "action to realize the intention" (performatory action) appears to be in contradiction to the unity of perception-action.

Exploration is Continuous and Multimodal: Exploring is Performing

Exploration Never Ceases

As considered in the previous section, the differentiation between exploratory and performatory actions has contributed important understanding in developmental studies (Adolph, 1995; Adolph et al., 1997, 2000; Adolph & Eppler, 1998), where infants face the task of perceiving whether to act or not (e.g., walking down slopes or walking over an unexpected surface). However, in numerous sports activities, performers are in continual need of adapting their ongoing activity and are, therefore, unable to necessarily stop and “explore” their environment. For example, performance in pole vaulting necessitates that athletes adjust the pole position whilst running at high-speed to accurately point the tip of the pole to the vault box, and then prospectively control when and how to move relative to the pole to convert maximal kinetic energy into gravitational potential energy while avoiding the bar. Indeed, performance environments are often dynamic and require to continuously perceive the opportunities for action relative to ongoing events (Fajen, 2005; Fajen, Riley, & Turvey, 2008).

The ability to anticipate future states of the individual-environment relation is a characteristic of all animals, especially skilled performers in sport (Araújo, Hristovski, Seifert, Carvalho, & Davids, 2017). For instance, in a series of recent climbing studies, Seifert and colleagues have found that performers do not appear to perceive the actions enabled by each separate hold during an ascent, but rather, they perceive a chain of movements offered by the properties of the holds and layout on the wall (L. Seifert et al., 2018; Ludovic Seifert, Cordier, Orth, Courtine, & Croft, 2017). Moreover, in dynamic environments such as soccer games, players may act by anticipating a chain of actions to score or defend, but they continuously need to probe for potential changes in the ball, teammates, and opponents’ movements that could affect the viability of their chain of actions (Dicks, Araújo, & van Der Kamp, 2019). The concept of nested affordances, which emphasizes that seemingly discrete behaviors are better understood as a continuous flow of actions distributed across different temporal and spatial scales, may, therefore, help to understand how individuals efficiently chain their actions to achieve a task-goal.

The concept of nested affordances was further developed by Wagman (2012), who demonstrated the effect of practice on the estimation of reachability, revealing that affordance perception depends on the future states by which a behavior will occur. Specifically, Wagman, Cialdella and Stoffregen (2018) proposed that affordances can be nested in a hierarchy that consists of three levels: the "Why" level, which represents the task goal; the "What" level, which represents the specific behaviors needed to achieve the task goal; and the "How" level, which represents the various means available to achieve the task goal (Wagman et al., 2018; Wagman & Morgan, 2010). For illustration, Wagman (2012) showed that individuals could estimate their maximum touching height (the "Why" level) when they were asked to reach a suspended object (the "What?" level) by (i) standing on toes or standing with heels touching the ground, (a first "How?" level), and/or by (ii) using (or not using) a tool (a second "How?" level). These results indicate that individuals are able to perceive the future state of their action capabilities even when they are about to perform a series of nested actions. Therefore, there is not an exploratory action that dictates what and how to do the next performatory action, but exploration enables performers to keep on accurately perceiving and acting.

In accordance with the nested affordances perspective, we propose that exploration could also be considered as an aspect of performatory activity. For instance, in a team sport such as soccer, the player in possession is not the only sportsperson on the field "performing". All the other players are also acting in such a way that they seek to probe future actions, and at the same time, they move to create opportunities for passes or to restrict opportunities (depending on whether their team is in possession of the ball or not). Thus, performers in team sports are constantly scanning, probing and acting in their environment in such a way that the differentiation between exploration and performatory periods is ambiguous. Moreover, when a performer tries to dribble past his/her opponent, he/she may use deception to influence his/her opponent and guide future actions. That is, as the player is revealing and picking up information, he/she is also generating information. Thus, expertise may reside in the continuous exploratory activity of performers that enables them to maintain an active prospection of the available information to act effectively (Pocock et al., 2019). In sum, the prospective control of action occurs through the information-movement coupling, which enables to continuously adjust the relation between individual and environment to achieve the task-goal (Araújo et al., 2017). On-going actions reveal information that contribute to perception of affordances related to this action (Franchak, van der Zalm, & Adolph, 2010).

Exploration is multimodal

The continuity of exploratory activity is also dependent on multimodal perception. An important emphasis of James Gibson (1966) was that the environment is not perceived passively in which our actions are responses to stimuli, but that we actively perceive the world through the actions of the different perceptual systems. However, a multimodal account of exploration is lacking in the study of sport skill acquisition. Notably, visual exploration has largely been studied using video-based laboratory tasks where the opportunities for action are severely compromised and not representative of complex sport environments (Mann et al., 2007; McGuckian, Cole, & Pepping, 2018). Indeed, results have revealed that the gaze behaviors utilized by soccer goalkeepers when attempting to save penalty kicks change as a consequence of both the environment (i.e., video presentation vs. real-time opponent) and the response requirements (e.g., simulated movement vs. diving to save the kick) (Dicks, Button, & Davids, 2010).

Comparable to the study of sport performers, the role of exploration in the perception of affordances has also been studied in laboratory tasks, with restrictions placed on participant behavior. For instance, Pepping and Li (2008) investigated the role of visual and haptic exploration on the perception of maximum jumping height from different surfaces. One group of participants was allowed to explore visually and haptically (i.e., they were invited to jump on the different surfaces) whereas another group was limited to visual exploration. Although the haptic exploration group could access more information, they did not improve perception of their jumping capabilities. Rather, they overestimated their capabilities, whereas the participants in the visual exploration group underestimated them. Thus, the results indicate that limiting the perceptual systems during exploration, does not appear to support accurate attunement or calibration. Indeed, methods that have constrained the modes of exploration, have also been used to study the perception of "sit-ability" under different leg lengths (Mark, Balliett, Craver, Douglas, & Fox, 1990), gap "cross-ability" (Mark, Jiang, King, & Paasche, 1999), the "catchableness" of fly balls (Oudejans, Michaels, Bakker, & Dolné, 1996) and the minimum passing height of a barrier when using a wheelchair (Yu, Bardy, & Stoffregen, 2011; Yu & Stoffregen, 2012). In these studies, the limitations on the permitted actions with the different perceptual systems (e.g., notably the haptic system and visual system) has been shown to negatively affect the perceptual judgements of participants in comparison to conditions where they are able to freely explore. Such findings support a multimodal account of exploration and as such, examination of the temporal organization of different exploratory actions provides the opportunity to better understand how multimodal exploration can give rise to skilled perception-action.

Research conducted in the developmental psychology literature has highlighted the necessity of multimodal exploration by showing that the information picked-up through the different perceptual systems is used to support accurate affordance perception. For example, in the “walk on slope” experiment, Adolph and Eppler (1998) revealed that infants can obtain visual information about depth and slant, whilst haptic exploration is required to get information about friction. Furthermore, Adolph, Eppler, Marin, Weise, and Wechsler Clearfield (2000) described the exploratory activity of infants during the “walk on slope” task as a sequential process composed of three modes of exploration: exploration from a distance (e.g., looking at the slope); exploration via direct contact (e.g., touching the slope surface); and exploration of alternative means (e.g., crawling instead of walking). Following this idea of a sequential organization of exploration, Kretch and Adolph (2017) proposed that the mode and organization of exploration in space and time is relative to its cost in terms of effort, time, and injury risk. According to this hypothesis, individuals use the exploration modes following a ramping-up organization process. For instance, haptic exploration is a risky form of exploration because it involves direct contact with an unknown surface, thus, it is only used to obtain new information following less exposed forms of exploration such as visual exploration that can be achieved from a distance and, therefore, with limited risks. Thus, exploratory activity appears to be organized in space and time when individuals search for opportunities for actions. A closer look at how haptic, motor, and visual exploration are linked during tasks is required to reveal the organization and changes in organization of exploration to maintain prospective control during action.

Stoffregen, Mantel, and Bardy (2017) reinforced the importance of multimodal exploration by proposing that perception should be considered as emerging from a single perceptual system rather than from different perceptual systems. This idea follows the global array hypothesis, which proposes that the senses function as a single unit during (active) perception (Stoffregen & Bardy, 2001). Studies have shown that exploratory activity can reveal higher order information to perceive the absolute distance from a target object, which is composed of optic flow patterns and haptic/gravito-inertial stimulation (Mantel, Bardy, &

Stoffregen, 2010; Mantel et al., 2015). These results argue in favor of looking for organization in the different dimensions of exploratory activity rather than in isolated perceptual systems. For instance, affordance perception depends on information exploited by the eyes, head and whole-body in motion, as studies have shown that eye-height information is important for calibration of the perceptual system to perceive whether one can sit on a seat or fit through a doorway (Franchak et al., 2010; Mark, 1987; Mark et al., 1990). The information-movement couplings utilized during exploration may, therefore, provide individuals with the ability to act purposefully to reveal information. Subsequently, the usefulness of the revealed information depends on the organization of individuals' exploratory actions. Thus, exploratory activity is not only an information-gathering activity that occurs before the start of performatory actions, but it is embedded throughout the entirety of a performer's activity. Exploration is multimodal as individuals do not perceive the environment through isolated perceptual systems, but as a whole. From this whole, individuals must find functional patterns to discover affordances, which is made possible through attunement and calibration of the perceptual-motor system. But how can performers become sensitive to properties of their performance environment? How does exploration evolve with practice and experience in a task?

Exploration During Practice: Learning to Reveal Information

Dynamics of Exploration: Toward Less Exploration with Practice?

When exploration is investigated as a sequence of information-gathering actions, research has shown that exploratory activity tends to decrease with practice, and performatory activity also decreases as individuals attune to more reliable information and become more skilled in the task (e.g., Seifert, Boulanger, Orth, and Davids 2015). Quantification of exploratory actions has been studied during climbing, within which participants were instructed to climb three different routes - with different orientations of handholds – as fluently as possible (Orth, Davids, & Seifert, 2018; L. Seifert et al., 2015). In these studies, the handhold orientation in the climbing route and experience of participants in the task impacted the amount of exploration of climbers. Specifically, the number of exploratory actions decreased with practice and increased with the complexity of behavior specified by the climbing routes. Similar findings have been observed in the development of tool creation (van Dijk & Bongers, 2014). In this study, van Dijk and Bongers differentiated between distinct periods during task completion: (i) a visual phase; (ii) a manual and visual exploration phase; and (iii) a construction phase. The first two phases were considered as exploratory activity while the construction phase was related to performatory activity. The distinction between the exploratory and performatory periods was defined relative to the initiation of a movement that was aimed at achieving the task (i.e., to create and use a tool with the pieces provided). The duration of the two exploratory periods decreased with practice, whilst actions during these phases were found to be more goal-directed, as the actions were oriented towards constructing the final tool. The authors concluded that actions became more goal-directed with the attunement of the participants to their environment and the discovery of new possibilities for action. In sum, these findings suggest that the amount of exploration decreases as the performers become better attuned to relevant information about affordances.

However, focusing analysis solely on the amount of exploration may be misleading. For example, Wagman, Shockley, Riley and Turvey (2001) examined how the accuracy of participants' estimations of the width and height of different objects differed following periods of haptic exploration completed under different modes of practice (i.e., with or without knowledge of results). Results revealed that irrespective of the feedback received, exploration time and exploration complexity (e.g., randomness in hand movements) decreased, which suggests that exploration decreased and gained in goal-directedness (cf. van Dijk and Bongers 2014). Nevertheless, attunement did not occur for the groups without knowledge of results; in this case, the decrease in exploration time was not associated with improved performance in the size estimation of objects. This finding is in line with infant locomotion studies, which have reported that neither the amount nor the type of exploration predicts motor decisions (Adolph et al., 2000; Joh & Adolph, 2006; Kretch & Adolph, 2017). Therefore, an increase in the effectiveness of exploration cannot be explained solely through the measurement of the quantity of exploration; a measure that accounts for the accuracy of perception is required.

The literature considered in this section suggests that individuals who become successful in a task do not necessarily decrease the quantity of exploration over time. Rather, it appears that successful exploration reveals the opportunities for action that fit both an individual's action capabilities and properties of the environment. Thus, successful exploration guides the pick-up of reliable information for task accomplishment; that is, successful exploration is a consequence of increasing accuracy rather than decreasing quantity. Thus, we argue in the following sections that when studying the perceptual learning processes of attunement and of calibration, it is more insightful to investigate changes in performers' exploration during practice rather than the volume of exploration.

Explore to Reveal Reliable Information: Differentiation of Information

Perceptual learning studies have demonstrated that, with practice, novices can learn to exploit more reliable informational variables through the attunement of the perceptual systems (Jacobs & Michaels, 2006; Smith, Flach, Dittman, & Stanard, 2001; van der Kamp, Savelsbergh, & Smeets, 1997). To better understand the relation between exploration during learning and task achievement, an important question is whether the changes in the pick-up of information are a consequence of changes in the mode of exploration. For instance, van Dijk and Bongers (2014) observed the functional reorganization of gaze behavior with practice in their tool making task. This reorganization had both an exploratory role, which led to the pick-up of information about affordances, and a performatory role, which led to alterations of the environment that led to the discovery of new affordances. Given the mutuality of perception-action, changes in the information exploited may be assessed by the changes in the way individual interacts with the environment. For example, Withagen, Kappers, Vervloed, Knoors and Verhoeven (2013) investigated if sighted, and blind children and adults were using the same exploratory actions to differentiate between dimensions of an object including the shape, weight, volume and texture. The experimenters defined five exploratory procedures that they used to code the participants' hand movements. They measured the percentage of time spent using each exploratory pattern and the quality of exploration (i.e., the time needed before an estimation). Results showed that specific exploratory patterns were necessary to estimate some dimensions of the objects and that the difference between sighted and blind participants was not a result of the specific exploratory pattern utilized but in the quality of exploration (i.e., blind participants needed less time to respond). With practice, participants learnt to differentiate three out of four object dimensions (i.e., their shape, texture and volume but not their weight), which illustrated that practice led to the detection of more reliable information. Thus, the novice participants needed to find an adequate means of exploration to interact with the objects to achieve the task and, as such, they learnt how to explore.

Wagman (2012) pointed out that changes in exploratory actions can be obvious (e.g., like touching a surface to estimate its walk-ability after a fall, Joh and Adolph, 2006) or more subtle (e.g., changes in head and torso motion are sufficient to judge maximum sitting height when action capabilities are changed: Stoffregen, Yang, and Bardy, 2005). In accordance with different contemporary learning perspectives in ecological psychology (Fajen, 2005; Jacobs & Michaels, 2007), it would be important to understand whether differences exist in the modes of exploration associated with changes in perceptual attunement and the calibration of action. An example of an obvious change in exploratory activity was observed in a study by Joh and

Adolph (2006) during which, children had to walk on a path with a hidden foam pit. Results showed that after falling in a trial, children increased the amount of exploration on subsequent trials: they took more time before walking on the path, they changed their locomotor behavior, and they increased the use of exploratory touching near the foam pit. Task achievement was due to the differentiation of reliable visual information (i.e., the delineation of the new ground surface), which was motivated by a fall in an earlier trial that guided changes in the exploratory and locomotor activity. Exploration may lead to misperception and failure in the task if the exploited information is not reliable, irrespective of the time spent exploring the environment (Adolph, Marin, & Fraisse, 2001). Therefore, the quantity of exploration during learning should be investigated alongside the mode of exploration (i.e., how do individuals reveal information to achieve the task?) and the dynamics of exploration during practice (i.e., what were the previously observed outcomes and behaviors?).

A recent climbing study proposed an innovative method to study the dynamics of exploration during the acquisition of a complex motor skill. To describe the temporal organization of exploration of climbers during practice, Seifert, Orth, Mantel, Boulanger, Hérault, and Dicks (2018) defined five different climbing states: (i) looking at the route; (ii) adjusting the center of mass; (iii) determining which hold to use (i.e., modifying the position or orientation of the hand or foot); (iv) hold changing (i.e., grasping another hold while the hip stays stationary before motion); and (v) moving the hip and at least one limb. The number of times each mode was used, and their relative duration was measured for each trial during practice. The authors presented the dynamics of exploration across multiple temporal levels, which enabled improved understanding on the relations between exploration during learning and task achievement. Their results revealed that climbers decreased the number of stationary states while their climbing fluency increased, suggesting an improvement in “route finding” skill, encompassing the ability to perceive a chain of movements (i.e., nested affordances) on the climbing route. Such association between the dynamics of exploration and the dynamics of performance highlights changes in the efficiency of an individual's exploration. The analysis of the dynamics of the efficiency of the exploratory activity would also reveal if the learning protocol enabled individuals to learn to explore effectively, that is by guiding performers toward information about affordances relevant for the task achievement.

Explore to (Re)Calibrate the Perceptual-motor System: Scaling Action to the Information

Although the previous section stressed that the exploration of performers may change as they increase their sensitivity to their environment, it shouldn't be forgotten that the accurate perception of affordances is grounded in the individuals' sensitivity to their action capabilities (Fajen, 2007). For example, Oudejans, Michaels, Bakker, and Dolné (1996) used an interception task to study the "catchableness" of a fly ball. To be perceived, this kind of affordance requires that participants scale information to their body size (e.g., eye height and leg length) and to their running and catching capabilities. Results revealed that participants were more efficient in judging the ball "catchability" when they could move than when they stood before giving their judgement. This difference was explained by the availability of information about the boundaries of the participants action capabilities when they are moving, which supports the view that exploration is continuous.

Given that action capabilities are liable to change due to motor development on a longer timescale, and on a shorter timescale, due to fatigue, calibration and recalibration must be continuous to accurately perceive opportunities for action (Franchak & Somoano, 2018). More specifically, a change in action capabilities modifies the mapping between information and action which requires recalibration, that is, to adapt the scaling of action to information (van Andel, Cole, & Pepping, 2017). Moreover, Brand and de Oliveira (2017) proposed that the exploration required for recalibration depends on the availability of reliable information and on the magnitude of the disturbance of the action system. The authors subsequently suggested that expert performers may better adapt to disturbances in their action capabilities as they may have developed exploratory actions that support recalibration over a relatively short timescale (Brand & de Oliveira, 2017). For example, Mantel, Stoffregen, Campbell, and Bardy (2015) demonstrated that individuals could generate sufficient information about the distance between themselves and an object with only a combination of eye, head and torso movements. Such adaptive exploratory actions could reflect the subtle changes in exploration that we previously discussed that are used to adapt perception and action to the context (Wagman, 2012).

During development, children adopt different locomotion patterns including crawling and walking due to postural milestones (e.g., learning to crawl, to walk…), which requires calibration of an infant's action capabilities and contributes to the process of differentiation of information (Adolph et al., 1997; Adolph & Eppler, 1998). Indeed, experiments on the slope crossing task have revealed that infants in their first weeks are unable to judge risky slopes. Rather, they needed weeks of locomotor experience to develop exploratory activity to generate information that reveals the fit between environmental properties and their capabilities (Adolph, 2008). In fact, the emergence of new coordination modes can increase individual action capabilities and extend the field of possibilities that the environment offers to individuals. During learning, changes in patterns of coordination used to achieve task outcomes have been observed during practice (Chow, Davids, Button, & Rein, 2008; Komar, Potdevin, Chollet, & Seifert, 2019; Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003). These behavioral dynamics may induce the need for learners to modify their exploratory activity to control their movements accurately, but it also gives to the learners the chance to discover new opportunities for interaction with the environment.

It has been suggested that the discovery of original and functional possibilities for action (i.e., individuals' creativity) may be enhanced when individuals act close to their maximal action capabilities (Orth, van der Kamp, Memmert, & Savelsbergh, 2017). Conversely, it has been proposed that in everyday tasks, individuals tend to stay in a safe region in-between the boundaries of their action capabilities to preserve the possibility to adapt their behavior (Fajen, 2005). For instance, studies show that children playing in a climbing playscape stay within a safe region of their action boundaries and keep a security margin when they climb (Croft, Pepping, Button, & Chow, 2018; Prieske, Withagen, Smith, & Zaal, 2015). This protective behavior has also been observed in a virtual car braking task where participants anticipated braking even if they could stop later (Fajen, 2005; Fajen & Devaney, 2006). However, in competitive sport contexts, performers are pushed toward their action boundaries. In such instances, exploratory movements (i.e., like touching a hold in a climbing task to estimate its grasp-ability) may be limited so that performers are targeted in their exploration to maintain a prospective control and to perceive the limits of their action capabilities. For example, when attempting to save penalty kicks, soccer goalkeepers tend to initiate movements to intercept the ball outside of their action boundaries (Dicks, Davids, & Button, 2010). Although this late dive may not enable goalkeeper to reach for the ball if the shot is highly accurate, this timing of action allowed goalkeepers to rely on more useful spatial information to anticipate kick direction. Thus, methods that investigate affordance-based control of action should assess the maximal action capabilities of the performers to examine whether they are sensitive to their action boundaries. Also, it seems that performers should explore a large range of their action capabilities during practice to develop efficient exploratory activity, and acting close to their action boundaries may encourage performers to find new movement solutions that would extend their maximal action capabilities and their possibility of exploration.

Learning to Explore

A key emphasis of this critical review is that skill learning conditions in sports should encourage the development of modes of exploration that reveal the fit between environmental properties and performers' action capabilities to perceive affordances relevant for task achievement. Practice conditions should: (i) lead performers to develop exploratory activity that reveals more reliable information; and (ii) encompass safe environments where performers can learn to explore even when they behave close to – and beyond - their current maximal action boundaries. When applied to climbing, a safe environment refers to situations from which the learner can escape, fallback or adapt and use a back-up plan. To test this hypothesis, Seifert, Boulanger, Orth, and Davids (2015) designed three climbing routes by manipulating the hold orientation and the number of available edges for grasping during learning. A horizontal-edge route was designed to allow horizontal holds in which the trunk faced the wall. A vertical-edge route was designed to allow vertical holds, which experienced climbers were able to grasp with the side of their body toward the wall. Finally, a double-edge route was designed to invite both horizontal and vertical holds. Because a route with only vertical-edge holds was challenging for novice climbers, the double-edge route allowed safe and functional exploration because climbers could both exploit their preexisting behavioral repertoire (i.e., horizontal-hold grasping pattern with their trunk toward the wall) and explore new behaviors (i.e., vertical-hold grasping with their side toward the wall). The results indicate that this safe environment of practice can be useful because perceptual-motor exploration appears less risky, with possible back-up and the learner is more inclined to experiment in these regions (L. Seifert et al., 2015). Thus, this learning design guided the exploration of learners to search for reliable information to perform the vertical-hold grasping.

However, research has also demonstrated that if there is insufficient variation in the practice environment, learners can sometimes exploit information that does not support accurate perception when they are exposed to a broader range of situations (Fajen & Devaney, 2006; Smith et al., 2001). To address this issue, Smeeton, Huys and Jacobs (2013), proposed a novel type of intervention to guide learners' exploration to pick-up more reliable information by neutralizing less useful information. More specifically, they reduced the usefulness of the informational variables that were potentially used by novice tennis players to anticipate the direction of their opponent's stroke by keeping constant this potential information while the strike outcomes were varied. Two important findings revealed that: (i) learners exploited new information if the usefulness of the initial information is reduced; and (ii) learners could attune to higher order information that supported accurate perceptual-motor skill in both a post-test and transfer test (in this study, the higher-order information was distributed across different body parts of the opponent).

Variable practice has been proposed to guide learners' perceptual attunement and to enhance transfer of learning (Fajen, 2005; Fajen & Devaney, 2006; Huet et al., 2011). In this form of practice, less useful informational variables are varied across practice trials so that learners are forced to search for new and more consistent information to guide their action. Smith, Flach, Dittman, and Stanard (2001) proposed the concept of flexible attunement to describe the ability of learners to rely on different informational variables according to the performance context. Fajen and Devaney (2006) observed such flexible attunement while comparing the effects of different variable practice conditions to perform a braking task in a virtual environment. They manipulated either (or both) the stop sign radius and/or the initial speed of the virtual vehicle so that the less reliable informational variables, like the expansion rate of the sign would no longer be useful. Results showed that these interventions led to perceptual attunement: participants learnt to rely on high order informational variables to guide their actions. Similarly, Huet, Jacobs, Camachon, Missenard, Gray, and Montagne (2011) created a flight simulator where the less reliable informational variables initially used by novice participants were varied so that exploiting this information no longer supported accurate action. Results showed that participants in the variable practice group outperformed a constant practice group in a transfer test due to changes in the informational variables used to guide action. Developing interventions that support flexible attunement (i.e., transfer in the use of a variable to guide action) is important in sports given the variable and complex nature of sport environments (Fajen et al., 2008). Dicks, Pocock, Thelwell, and van der Kamp (2017) proposed a form of on-field variable practice to train goalkeepers in a penalty task. The goalkeepers faced three players that started their run-up together but only one them executed the penalty on each trial. This intervention was aimed at directing the goalkeeper's attention to information that emerged around the time of when the penalty taker's foot contacted the ball. Compared to constant practice (i.e., facing penalty kicks from one player executing the run-up and penalty), the intervention enhanced performances of goalkeeper on non-deceptive penalty kicks, which may be due to a better perceptual attunement. Such intervention must be developed to help learners to pick-up more reliable information about affordances, and so that the exploration developed during practice can be transferred and used to achieve high performances outside the training context.

Linking perspectives from ecological psychology to existing findings on the dynamics of learning may help to better understand the transfer of perceptual-motor skills to multiple contexts of performance and to inform interventions that both develop a performer's motor repertoire and guide learners toward more reliable information. Indeed, a large volume of the literature focusing on interventions in performance contexts is rooted in the dynamical systems approach to learning (Schöner, Zanone, & Kelso, 1992). This framework has focused on the effect of the interventions on coordination dynamics (i.e., the motor repertoire of the learners) rather than on perceptual attunement (Chow et al., 2008, 2007; Lee, Chow, Komar, Tan, & Button, 2014). Based on Bernstein's (1967) observation that practice is a form of "repetition without repetition", interventions have focused on the role of movement variability to develop the adaptability of learners. For instance, training interventions such as "differential learning" have proposed to add random noise to task constraints (i.e., irrelevant movement components) to increase the performance of learners by discovering multiple movement solutions (Schöllhorn et al., 2006; Schöllhorn, Hegen, & Davids, 2012; Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009). A question remains about the qualitative nature and actual relevance of the induced variability (i.e., the random noise in the task constraints). Indeed, variations in the learning contexts may encourage attunement only if reliable information is available in the different learning conditions (Smeeton et al., 2013). Cardis, Casadio, and Ranganathan (2018) have also pointed out that such variability may increase exploration of new solutions but may adversely affect the ability to retain the learned solution, thus, they questioned the threshold of variability after which variable practice impairs learning.

In summary, learning interventions may promote the discovery of exploratory actions that enhance the transfer of perceptual-motor skills. Learners should be given the opportunity to safely explore and to be guided toward more reliable information for action. Reducing the usefulness of the less reliable information seem to be effective in enhancing transfer of learning. In this aim, the less reliable information can be neutralized or varied across practice trials so that learners search for new and more reliable information for action. However, care must be given to the context of practice that may limit the opportunity to interact with the environment. Thus, as learning is not about accumulating information across trials but rather generating and exploiting useful information for action, interventions must lead performers to learn to explore rather than learning a model of skill.

Conclusion

This critical review focused on how exploratory activity can support the development of perception-action during learning. We considered that exploration is continuous and multimodal, and so, the generation and pickup of information lies in all the actions of performers. Therefore, we propose that future investigations in skill acquisition should look at the changes in the organization of the learners' exploratory activity in relation to performance achievements rather than observing the amount of exploration during practice. Experts in high-performance contexts such as sport manage to perceive future states of their relationship with their environment even though they experience changes in their action capabilities or events. Therefore, a dynamic view of exploratory activity may reveal how experts in sport act in uncertain and dynamic environments. Practice conditions must lead individuals to adopt exploratory activity that reveals the fit between the environmental properties and their action capabilities. Moreover, to discover new opportunities for action, learning environments should promote safe conditions that give performers the opportunity to develop exploratory activity, even when they act outside of a 'safe region' of their action capabilities. In this regard, interventions that guide learners to search for more reliable information appear to be the most suitable learning design to develop exploratory activity that would enhance the transfer of skill to various performance contexts.

Compliance with Ethical Standards

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